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The Thermodynamic Ocean Prediction System (TOPS) uses Mellor-Yamada Level II mixing [1] and Ekman dynamics to forecast upper-ocean mixing and wind-drift advection. The U.S. Navy's Fleet Numerical Oceanography Center (FNOC) cycles TOPS with its operational, upper-ocean, thermal analyses for several regional areas. These include the northern and southern hemispheres, the eastern and western Mediterranean, and the Norwegian Sea. The analyses (or nowcasts) provide initial conditions to TOPS. The TOPS 24 hr. forecast, in turn, provides first-guess information to the following day's nowcast. TOPS thus provides up to three-day forecasts of the upper ocean thermal structure as well as an extra source of upper ocean information to the thermal analyses in data sparse areas.

Present versions (TOPS and TOPS 2.1) limit applications to 63x63 grids associated with the standard FNOC polar stereographic grids. TOPS 3.0, a major upgrade developed at the Naval Ocean Research and Development Activity (NORDA) and presently being implemented at FNOC, expands the application potential of TOPS. Greater modularity and reoriention of the major TOPS pre- and post processing to the 4-pipe Control Data Corporation CYBER 205 super-computer allows larger, variable-dimension grids.

We present results of TOPS 3.0 applied to the FNOC 125x125 mid-Pacific region ($\sim$50 km. resolution). Included are examples of the regional Diurnal Ocean Surface Layer model contained within the TOPS 3.0 run stream. This model provides additional information on diurnal variability within the mixed layer based on [2]. We also consider some near-term future upgrades to TOPS 3.0.

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TOPS 3.0: AN UPGRADE TO OCEAN THERMAL ANALYSIS AND PREDICTION AT FNOC

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ABSTRACT

The Thermodynamic Ocean Prediction System (TOPS) uses Mellor-Yamada Level II mixing [1] and Ekman dynamics to forecast upper-ocean mixing and wind-drift advection. The U.S. Navy's Fleet Numerical Oceanography Center (FNOC) cycles TOPS with its operational, upper-ocean, thermal analyses for several regional areas. These include the northern and southern hemispheres, the eastern and western Mediterranean, and the Norvegian Sea. The analyses (or nowcasts) provide initial conditions to TOPS. The TOPS 24 hr. forecast, in turn, provides first-guess information to the following day's nowcast. TOPS thus provides up to three-day forecasts of the upper ocean thermal structure as well as an extra source of upper ocean information to the thermal analyses in data sparse areas.

Present versions (TOPS 1.0 and TOPS 2.1) limit applications to 63x63 grids associated with the standard FNOC polar stereographic grids. TOPS 3.0, a major upgrade developed at the Naval Ocean Research and Development Activity (NORDA) and presently being implemented at FNOC, expands the application potential of TOPS. Greater modularity and reorientation of the major TOPS pre- and postprocessing to the 4-pipe Control Data Corporation CYBER 205 super-computer allows larger, variable-dimension grids.

We present results of TOPS 3.0 applied to the FNOC 125x125 mid-Pacific region (~50 km. resolution). Included are examples from the regional Diurnal Ocean Surface Layer model contained within the TOPS 3.0 run stream. This model provides additional information on diurnal variability within the mixed layer based on [2]. We also consider some near-term future upgrades to TOPS 3.0.

1. INTRODUCTION

Operational forecast models of upper-ocean thermal structure can provide important environmental information in areas ranging from fisheries to search and rescue to underwater acoustics. The U.S. Navy has been a leader in this technology since the late 1970's. In 1983, Fleet Numerical Oceanography Center (FNOC) began the first, operational, real-time, upper-ocean thermal structure forecasts with the implementation of the Thermodynamic Ocean Prediction System (TOPS). Developed by the Naval Ocean Research and Development Activity (NORDA), TOPS provides real-time global and regional, upper-ocean forecast capability out to 72 hours [3].

2. MODEL AND MODEL OPERATION

Initialized by an objective analysis scheme which combines climatology with all available ship, satellite, and bathythermograph data, TOPS generates daily, 72-hour, upper-ocean (0-400 m.) thermal forecasts. TOPS uses FNOC's operational atmospheric general circulation model, the Naval Operational Global Atmospheric Prediction System (NOGAPS) [4], to provide forecast heat, moisture, and momentum fluxes for model forcing.

The basic physics within TOPS consists of the conservation of heat, salt and momentum. Two notable features are: (1) the use of Mellor-Yamada Level II closure [1] in the vertical mixing terms for heat and salt and (2) the absence of pressure gradient terms in the momentum equations. Advection thus results from the wind-drift terms (Ekman and inertial) only, under the assumption that on the 1-3 day time scale of the forecast and away from strong western boundary currents, the geostrophic flow is of secondary importance. Vertical advection results from Ekman divergence. The major advantage incurred in the neglect of the pressure gradient terms is the lowered sensitivity of the model to initial conditions since the geostrophic adjustment process is eliminated.

The TOPS 24 hr. forecast also feeds back into the following days objective analysis as a first guess. This cycling helps fill in data sparse areas in the analysis by forcing changes in the analyzed field due to the known effects of atmospheric forcing on the upper-ocean. Further details on the cycling as well as TOPS physics are available elsewhere [3,5,8].

Two versions of TOPS are presently operational. TOPS 1.0 is a non-advective version which runs on 63x63, 40 km., polar-stereographic grids for both the eastern and western Mediterranean. TOPS 2.1 is the advective TOPS available on 63x63, 320 km. northern and southern hemispheric grids and on the Norwegian Sea on a 40 km. grid. The northern hemisphere TOPS runstream also contains a forecast of diurnal surface heating called the Diurnal Ocean Surface Layer (DOSL) model [2,6]. DOSL provides forecasts of diurnal warming which can result in the acoustic "afternoon effect" [7].

A geostrophic component of the horizontal advection is also included in the northern hemisphere TOPS. This component is derived from applying the thermal wind equation to the climatological density field. Noise introduced by the climatological density fields is reduced by making the resultant field non-divergent via the application of a stream function-vorticity equation to the divergent currents.

TOPS 3.0, delivered to FNOC in 1988 and currently being implemented , provides a major upgrade to present capabilities. The first major improvement is the generalization of grid size from 63x63 to m x n accomplished by modularizing the code and shifting high demand (time and memory) portions of the TOPS code onto FNOC's Control Data Corporation CYBER 205 super-computer. The second major improvement involves the removal of region specificity within the TOPS code. Together, these two upgrades allow ready coupling of TOPS to all of the present FNOC operational, polar-stereographic, regional, thermal analysis grids. In addition, the DOSL model runs within the relocateable TOPS 3.0 run stream allowing the forecast of diurnal sea surface temperature (SST) changes on any FNOC grid. Finally, following [8], nowcast geostrophic advection can also be included in the TOPS forecast via the Analysis-Derived Advection (ADA) model. ADA applies the thermal wind equations to the TOPS initial temperature and salinity fields to provide a nowcast of the geostrophic current field. A stream function-vorticity equation is solved (as in the climatological calculation described above), to reduce noise in the velocity field. The solution of this equation is by succesive over-relaxation [9] with a relocateable solver developed for ADA which allows arbitrary land/sea configurations within the given regional domain. The use of ADA inherently assumes: (1) that the geostrophic equations are valid for the given region, (2) that persistence is a reasonable forecast for the geostrophic flow over the 72-hour TOPS forecast period, and (3) that the temperature and salinity fields are both realistic especially where salinity significantly modifies the density field.

3. RESULTS

TOPS 3.0 has been developed using the FNOC 125x125 mid-Pacific region as a prototype area. Figure 1 provides an example of the present thermal analysis at the surface for this region. The hash marks over land show the grid spacing of ~50 km. This particular analysis is for January 25, 1989. Figures 2a and b shows the surface atmospheric pressure and associated surface winds for January 25 and forecast January 27 respectively. One sees the deep low in the western north Pacific moving to the central Pacific and interacting with the low pressure system in the Gulf of Alaska during this two day period.

Using these forecast conditions (including the intervening 6 hourly) fields, a TOPS 3.0 forecast was run. Figures 3a and b give the resultant surface currents at the initial time and at the end of 48 forecast hours. Along with vertical density instability, the vertical shear of these currents drives the mixing within this model. These currents have the additional benefit of providing surface currents for search and rescue purposes (see deWitt, et al in this volume). The surface currents are highly correlated with the surface winds as expected. The Ekman and inertial currents have the potential of interfering both constructively and destructively, thus yielding unanticipated horizontal advection as well as vertical mixing. In this example, however, no obvious interference occurs.
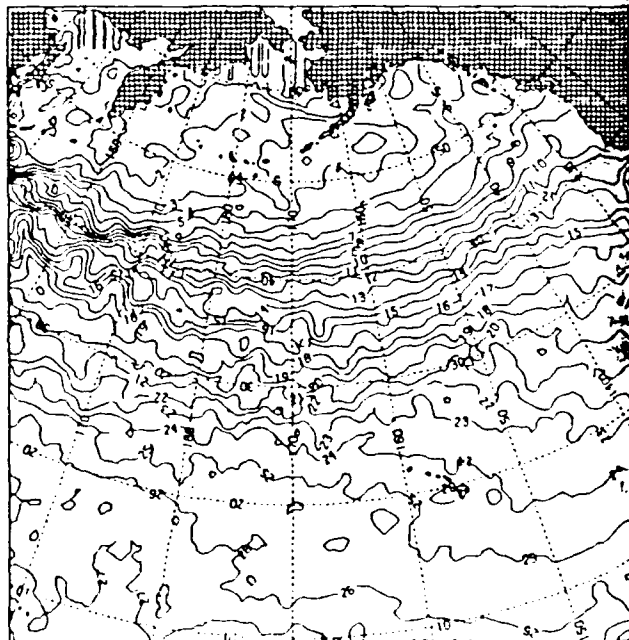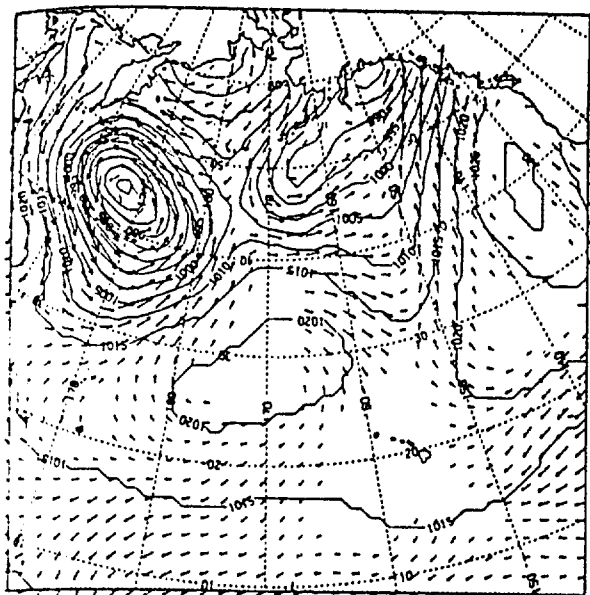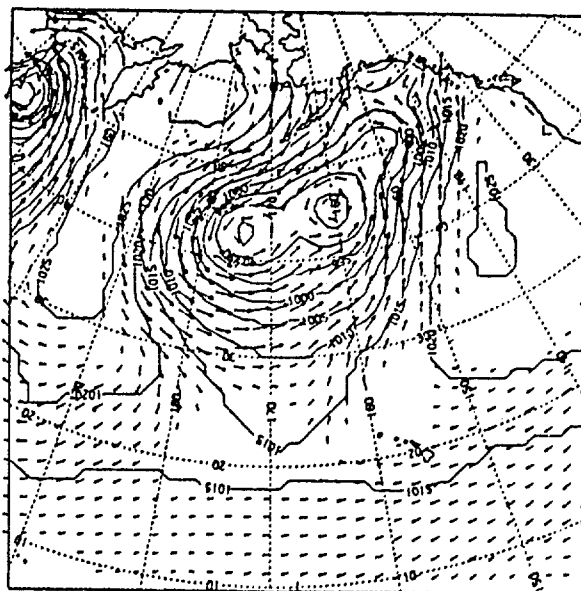

Figure 1. Sea surface temperature (°C) analysis on January 25, 1989 for the FNOC operational mid-Pacific region. Contour interval is 1°C. Grid spacing of ~50 km is shown hashed over land.
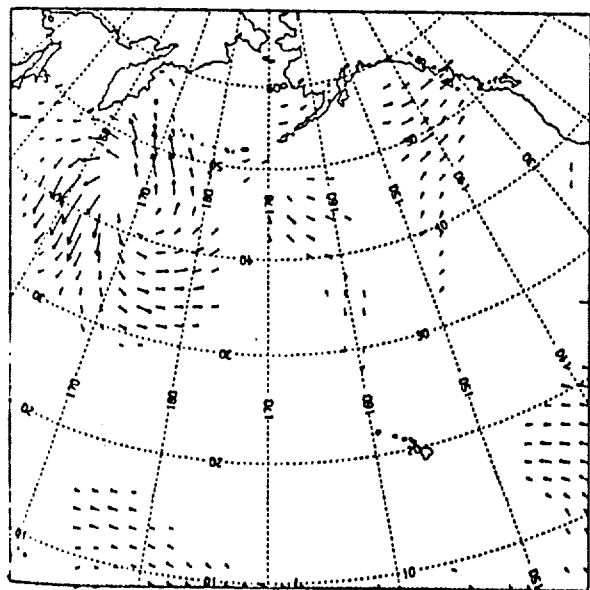
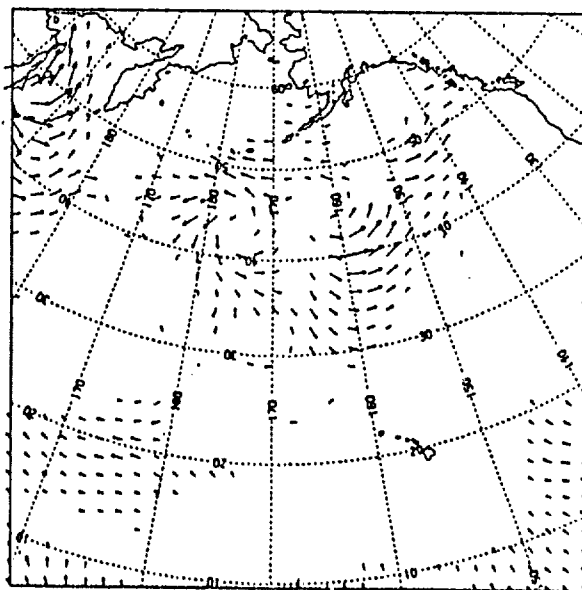(a)   (b)

Figure 2. NOGAPS sea surface pressure (mb) and surface wind (——→ = 50 m/s) on
January 25, 1989 interpolated to the FNOC mid-Pacific grid: (a) analysis, (b) 48 hr.
forecast. Contour interval is 5 mb. Winds below 5 m/s are not shown.

(a)   (b)

Figure 3. TOPS 2.0 surface currents (——→= 1 m/s) on January 25, 1989 for the FNOC
mid-Pacific grid: (a) initial time, (b) 48 hr. forecast. Vectors are plotted at every
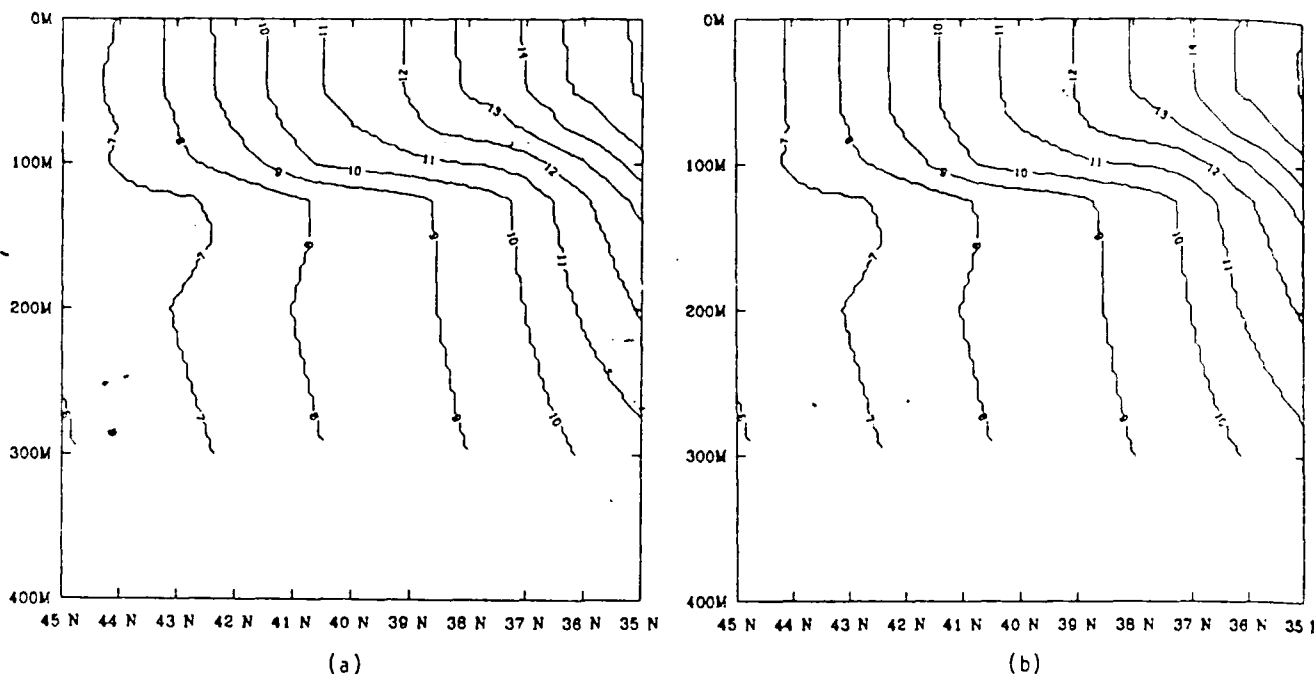fourth grid point. Currents below 0.05 m/s are not shown.

Figure 4. TOPS 3.0 temperature (°C) cross-section from 45 N, 155 W to 35 N, 155 W on January 25, 1989 for the FNOC mid-Pacific grid: (a) initial time, (b) 48 hr. forecast. Contour interval is 1°C.

To illustrate what TOPS produces in the vertical, figures 4a and b show a ten degree meridional cross-section across the sub-arctic frontal zone, again for the TOPS initial condition and TOPS 48 hour forecast respectively. The cross-section runs from 45 N to 35 N along the 155 W meridion. The temperature inversion at 150 m. north of 40 N shows the sub-surface location of the sub-arctic front to be between 40 and 41 N [10]. The surface manifestation of this front is not as clear. Due to this inversion, a subsurface sound channel with 150 m axis depth would be expected north of the front.

TOPS influence in this run, however, is limited to the upper 100 m. The increasing winds (figures 2a,b) through this region result in surface mixing throughout the region with deepening of the mixed layer only north of the front. At 44 N, an initial temperature inversion at the surface, due to cool, less saline water, is well mixed to 100 m within 48 hours. Acoustically, this mixing would change an initial, relatively-strong, surface duct into a weak or nonexistent duct.

The output from the DOSL model during the above run is shown for day 2 in figure 5. The areas of strong surface diurnal heating are about 10 degrees west of Hawaii with a maximum 2°C warming and 20 degrees west of California with maximum warming of 2.5°C. These results are consistent with the atmospheric conditions for this time. Figure 2b shows these areas underlying high pressure (with its expected high solar insolation) and low winds which together result in the diurnal warming.
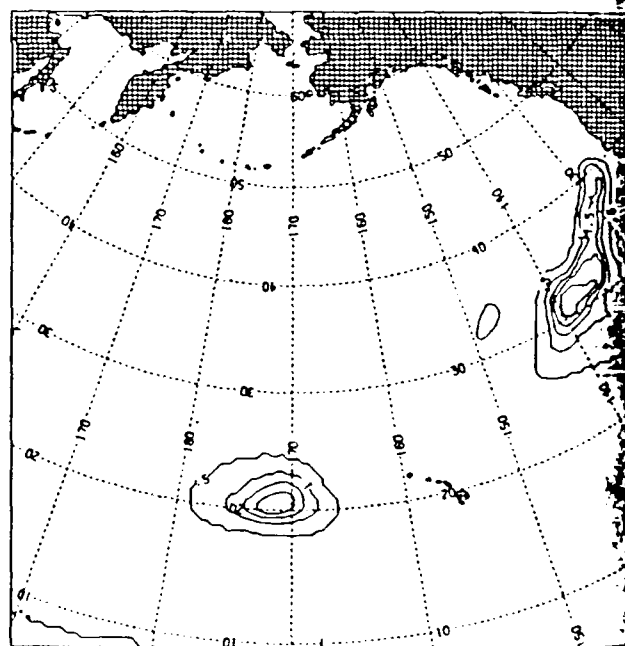

Figure 5. DOSL sea surface diurnal warming (°C) forecast for day 2 of January 25, 1989 TOPS 3.0 run. Contour interval is 0.5°C.

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ADA can also run on this region, however for a more dynamic example, we show ADA applied to the Gulf Stream. Figure 6 shows SST on the first of the new FNOC latitude/longitude regions which will replace the present operational polar stereographic regions [Clancy, 1988, personal communication]. This analysis was performed on February 2, 1989 on the 0.2 degree grid as shown hashed over land. The model qualitatively reproduces realistic meandering and gradients for the Gulf Stream front, its associated eddies and the shelf/slope front. Figure 7 gives a cross-section from 39 N, 75 W to 34 N, 70 W, across the shelf-slope front, the Gulf Stream and a partially submerged cold-core eddy. This indicates that the sub-surface structure is also qualitatively realistic. The detailed position and structure of these features results primarily from a twice-weekly front and eddy map provided to FNOC by the Naval Eastern Oceanography Command (NEOC). This map is derived using all available satellite (visible, infrared, and altimeter) data as well as ship and bathythermograph (BT) data [11]. Canonical models of eddy and frontal structure (feature models) are inserted in the appropriate locations within the analysis grid [12]. Actual data is then incorporated via optimal interpolation techniques [Cummings, 1988, personal communication; 13]. Salinities are then derived from known temperature-salinity relations for the region. Figure 8 illustrates the resultant non-divergent surface currents after applying ADA to the density field. Vectors are plotted at every other grid point. The maximum Gulf Stream surface velocities are realistic at about 1.5 to 2 m/s. The shelf-slope front, being density compensated, shows no flow. Continuous quality control, especially of the front and eddy maps, is essential for these products. A warm core eddy seen in figure 6 at 40 N, 58 W, has no subsurface manifestation resulting in no currents in figure 8 at this location. This occurs when the actual surface data available to the analysis shows the eddy but the front and eddy map and available subsurface data do not.

Figure 7. Temperature (°C) cross-section from 39 N, 75 W to 34 N, 70 W on February 2, 1989 for the new FNOC Gulf Stream analysis grid. Contour interval is 1°C.

Figure 8. ADA surface currents (⟶ = 2 m/s) derived from the February 2, 1989 temperature analysis on the new FNOC Gulf Stream analysis grid. Vectors are plotted at every other grid point. Currents below 0.15 m/s are not shown.

Quantitative comparisons of TOPS 3.0 with actual data will follow implementation of the various modules in their operational configuration but prior to their operational use. Due to the lack of adequate data sets for validation, cumulative statistical validations are performed during operational testing to assure the new products out-perform climatology, persistence, and the existing products [14]. Unassimilated BTs are differenced with model nowcast/forecasts
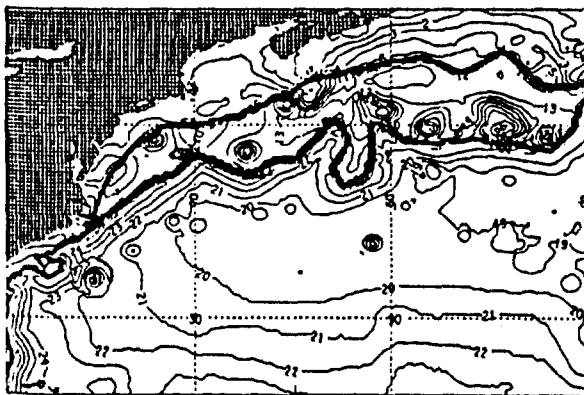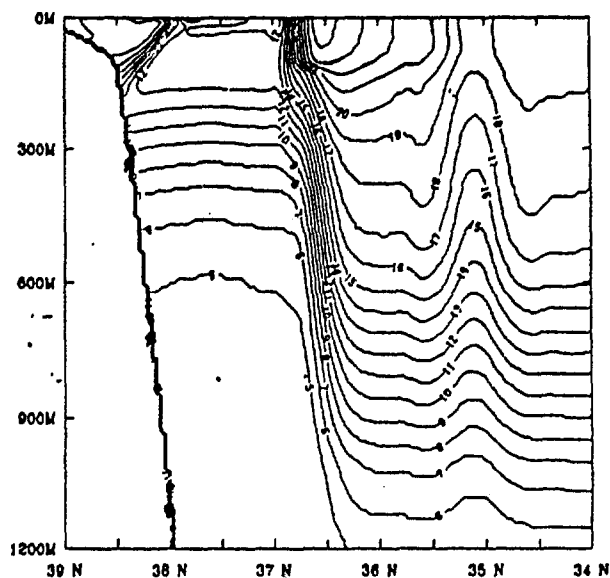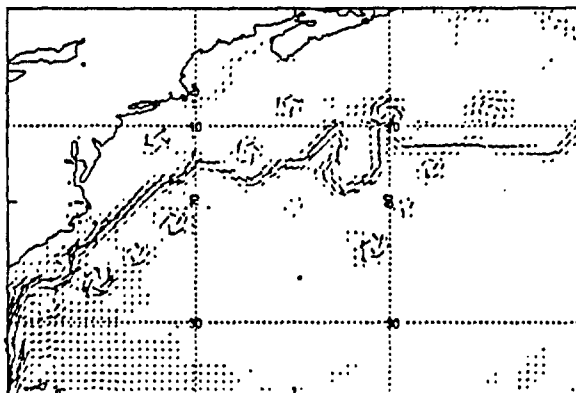

Figure 6. Sea surface temperature (°C) analysis on February 2, 1989 for the new FNOC Gulf Stream region. Contour interval is 1°C. Grid spacing of 0.2 degrees is shown hashed over land.

interpolated to the BT location. Accumulated over a month for a given region, these differences provide relevant statistics for evaluating model skill. Buoy drift relative to forecast currents are used to validate surface currents (see deWitt, et al in this volume).

4. SUMMARY

The flexibility of TOPS 3.0 holds the promise of more rapid implementation of coupled, upper-ocean, thermal nowcast/forecast models for the various FNOC operational regions. An upgrade underway this year (TOPS 3.1) will allow the application of TOPS to latitude/longitude grids consistent with FNOC's future direction in thermal analysis. A second upgrade begun this year will allow the eventual replacement of the nowcast geostrophic advection from ADA with forecast currents from a dynamic ocean circulation model such as the Ocean Circulation, Evolution, Assimilation and Nowcast System (OCEANS) [15]. NORDA has also developed a comparable TOPS/ADA system for shipboard use, Tactical TOPS (TTOPS), which allows relocateable applications on limited open-ocean areas [16]. TTOPS will likely not cycle with its analysis however due to rapidly changing regions of interest aboard ship.

5. ACKNOWLEDGMENTS

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